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THERMAL CONSIDERATIONS IN THE DESIGN OF DIVER'S SUITS

M. L. NUCKOLS

NAVAL COASTAL SYSTEMS LABORATORY
NCSL
PANAMA CITY, FLORIDA 32407

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NCSL

NAVAL COASTAL SYSTEMS LABORATORY

PANAMA CITY, FLORIDA 32407

CAPT JAMES V. JOLLIFF, USN
Commanding Officer

GERALD G. GOULD
Technical Director

ADMINISTRATIVE INFORMATION

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The basic components of heat loss from passive wet and dry suits are investigated. Changes in the thermal effectiveness of these components are shown with variations in the diver's environment. Critical design features are identified and their effects on suit insulation capabilities observed with environmental variations. An analytical model is developed to describe the thermal performance of diver's garments. Predictions are made for the thermal behavior of sample suit designs and compared with experimental values.

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INTRODUCTION

Underwater garments providing good, passive insulation* have been sought since the beginning of diving. This is primarily due to the ability of water to conduct heat from the human body approximately 25 times faster than air. In addition, water is capable of absorbing this lost body heat (capability determined by the product of density and specific heat) in quantities approximately 3500 times greater than air before a similar unit increase in temperature is recorded. As a result, unprotected divers can find a net heat drain from their bodies even in moderate $80^{\circ}F$ ($26.7^{\circ}C$) water temperatures. The body's ability to overcome this net heat drain, by surface vaso-constriction and increasing body heat production through shivering and increased activity levels, diminishes rapidly in effectiveness as water temperatures decrease. Figure 1 demonstrates this phenomenon with estimates of the endurance limits of divers with various activity levels, suit insulation values, and temperature differences between the skin and surrounding water. Endurance limits are based on the BUMED criteria which indicates a maximum net body heat drain of 200 Kcal before the diver's performance will be jeopardized.

Since engineers and physiologists often express the same physical parameters using different terms, thermal resistance or insulation in this study will be expressed in the unit clo. This widely accepted unit represents the thermal insulation afforded by an average suit of clothing with conversion factors as follows:

$$1 \text{ clo} = 0.88 \text{ ft}^2\text{-hr-}^{\circ}\text{F/Btu}$$

$$= 0.18 \text{ M}^2\text{-hr-}^{\circ}\text{C/Kcal} .$$

When thermal protection was called for in pre-World War II diving operations, the use of additional underwear was used in conjunction with the dry diver's dress, worn with the hard-hat breathing apparatus, until sufficient warmth could be achieved. This bulky suit satisfied, and continues to satisfy even today, the diver's needs for all but extreme conditions and hardly any other suit was used for over a century.

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*Passive insulation derives its thermal protection from the suit material. This contrasts with active protection from electric heating or circulating warm water.

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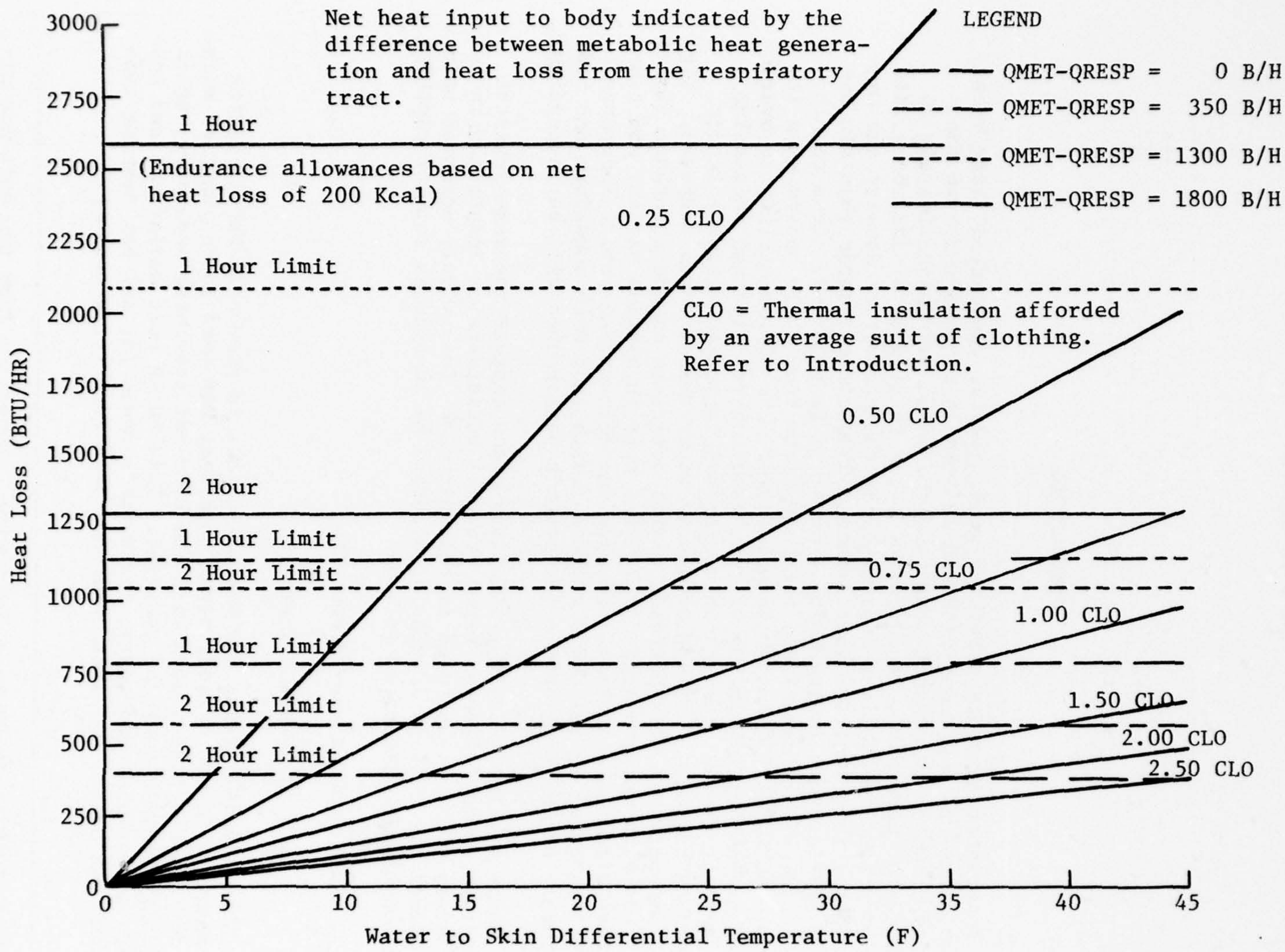

FIGURE 1. SUIT HEAT LOSS AND ENDURANCE LIMITS FOR VARYING INSULATION SUITS AND METABOLIC RATES

With the advent of scuba, the limitations of the bulky dry suit became evident and improvements were sought. These efforts often resulted in achieving less suit bulk while sacrificing insulation qualities and waterproof integrity. Even when operationally acceptable for short duration missions, the susceptibility of these lightweight "dry" outfits to leaks from defects, tears, and wear caused frequent annoyances.

In the early 1950's, a new approach was taken to the difficult problem of diver thermal protection. Tight-fitting, closed cell, foam rubber suits were designed to allow a thin film of sweat and water to exist between the suit and the diver's skin. The initial body heat loss serves to heat this small quantity of water, at which time the thermal gradient at the skin and its corresponding heat loss is reduced. The wet suit eliminates the problems of suit leakage and squeeze associated with the dry suits.

Good fitting, foam rubber wet suits have been found to give excellent thermal protection for shallow water diving for short durations even in polar regions. In fact, the wet suit serves today as the primary outfit for most commercial, military, and sport diving operations when scuba is used. However, the effectiveness of the foam rubber wet suit to retain diver body heat diminishes rapidly as depth increases. The compression of closed-cell foam caused by hydrostatic pressure acts simultaneously to decrease the material's resistance to heat flow for the original thickness (increases thermal conductivity) while reducing its thickness. This compound degradation in insulation value with depth causes 0.25-inch closed-cell foam to become as ineffective as a thin layer of 0.125-inch solid rubber in keeping a diver warm beyond approximately 8 atmospheres (70 m).

Therefore for deep dives or long duration missions, the use of either a noncompressible wet suit or dry suit with adequate thermal underwear is necessary. In either case, the need for auxiliary heat is evident in long duration dives. However, a good, passive thermal suit design is the key to an effective thermal protection system.

The basic components of heat loss for passive wet and dry suits, and their insulation effectiveness changes due to variations in the environment were investigated. Critical design features were identified along with their effects on suit insulation capabilities. An analytical model was developed to describe suit thermal performances to provide a prediction capability for future suit design work. Predictions were made for the thermal behavior of various sample suit designs and compared with experimental values.

SUIT COMPONENT INSULATION

The heat flow from a good fitting, passive diver's suit is primarily by conduction through the suit and undergarments, and by convection between the surface of the suit and its surroundings. Usually radiation and evaporation play an extremely small part in subsurface diver heat losses. It has been observed that the outside surface temperature of diver's suit is within 1 to 2°F of the ambient water temperature. The net heat transfer through such a suit can be described as

$$\dot{Q} = HA\,(T_s - T_\infty) \tag{1}$$

where

H = suit conductance (Btu/hr-ft^2-^{o}F) or (Kcal/M^2-hr-^{o}C)

A = surface area of suit (ft^2) or (M^2)

T_s = mean diver's skin temperature (^{o}F) or (^{o}C)

T_∞ = ambient water temperature (^{o}F) or (^{o}C) .

The suit conductance, H, is actually a composite of the conductances of each component layer of the suit, and is the inverse of the summation of the heat flow resistances of the suit components. For instance, the suit conductance of a diver's dry suit in Figure 2 made up of an outer garment, underwear, and some thin gas layer between the diver's skin and underwear can be described as

$$H = \frac{1}{R_{og} + R_{uw} + R_L + R_F} \quad \frac{1}{\frac{ft^2\text{-}hr^oF}{Btu}} \quad \text{or} \quad \frac{1}{\frac{M^2\text{-}hr^oC}{Kcal}} \tag{2}$$

where:

R_{og} = resistance to heat flow through the outer garment

R_{uw} = resistance to heat flow through the diver's underwear

R_L = resistance to heat flow through the thin gas interlayer

R_F = resistance to heat flow through film between diver's suit and surroundings (inverse of film coefficient, h_c) .

In the case of wet suits, R_{uw} will be eliminated and the resistance to heat flow offered by a thin gas layer, R_L, will be replaced with a thin layer of water.

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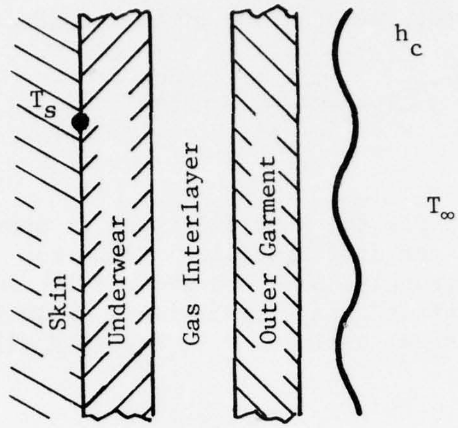
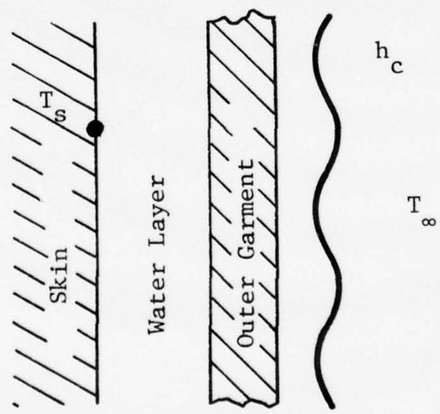


$$H = \frac{1}{R_{uw} + R_L + R_{og} + R_F}$$

DRY SUIT



$$H = \frac{1}{R_L + R_{og} + R_F}$$

WET SUIT

FIGURE 2. CONDUCTANCES OF DIVER'S SUITS (PASSIVE)

Since most of the human body components are basically cylindrical or spherical in shape, we must be careful in defining A in Equation (1). This is due to the form for the equation of heat conduction from a cylinder:

$$\dot{Q} = \frac{\Delta T}{\frac{\ln(r_2/r_1)}{2\pi K \ell}} = HA\Delta T \quad .$$

Figures 3 and 4 show that for the same thickness of insulation, the insulation value will vary for different size cylinders. In addition, the insulation values will strongly depend on whether the inside or outside radii are used in the surface area calculations. This problem can be avoided if the log mean area, $\bar{A}$, is used in Equation (1), where for the cylinders

$$\bar{A} = \frac{2\pi(r_2 - r_1)\ell}{\ln(r_2/r_1)} \tag{3}$$

r_1 = radius to inside surface of insulation

r_2 = radius to outside surface of insulation

ℓ = length of cylinder .

If the log mean area is used, suit components and the composite suit can be thought of as flat planes, thereby simplifying insulation calculations, since

$$\dot{Q} = \frac{\Delta T}{\frac{\ln(r_2/r_1)}{2\pi K \ell}} = HA\Delta T$$

if

$$A = \bar{A} = \frac{2\pi(r_2 - r_1)\ell}{\ln(r_2/r_1)}$$

then

$$H = \frac{K}{r_2 - r_1} = \frac{K}{L} \text{ and clo} = 1.136/H$$

where

L = insulation thickness.

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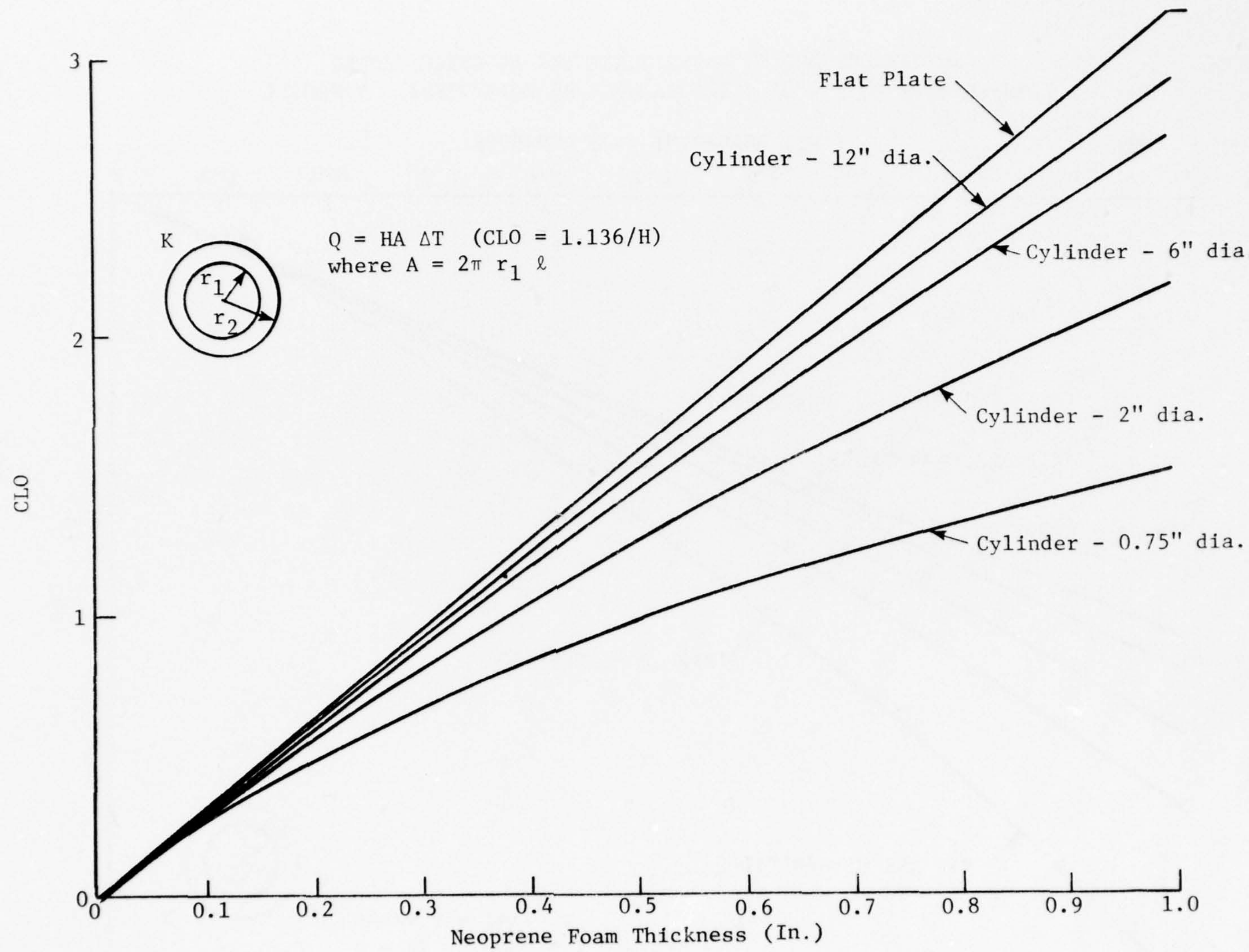

FIGURE 3. INSULATION OF FOAM NEOPRENE (K = 0.03 B/FT-HR-F) ON CYLINDERS AT SEA LEVEL BASED ON INSIDE RADIUS

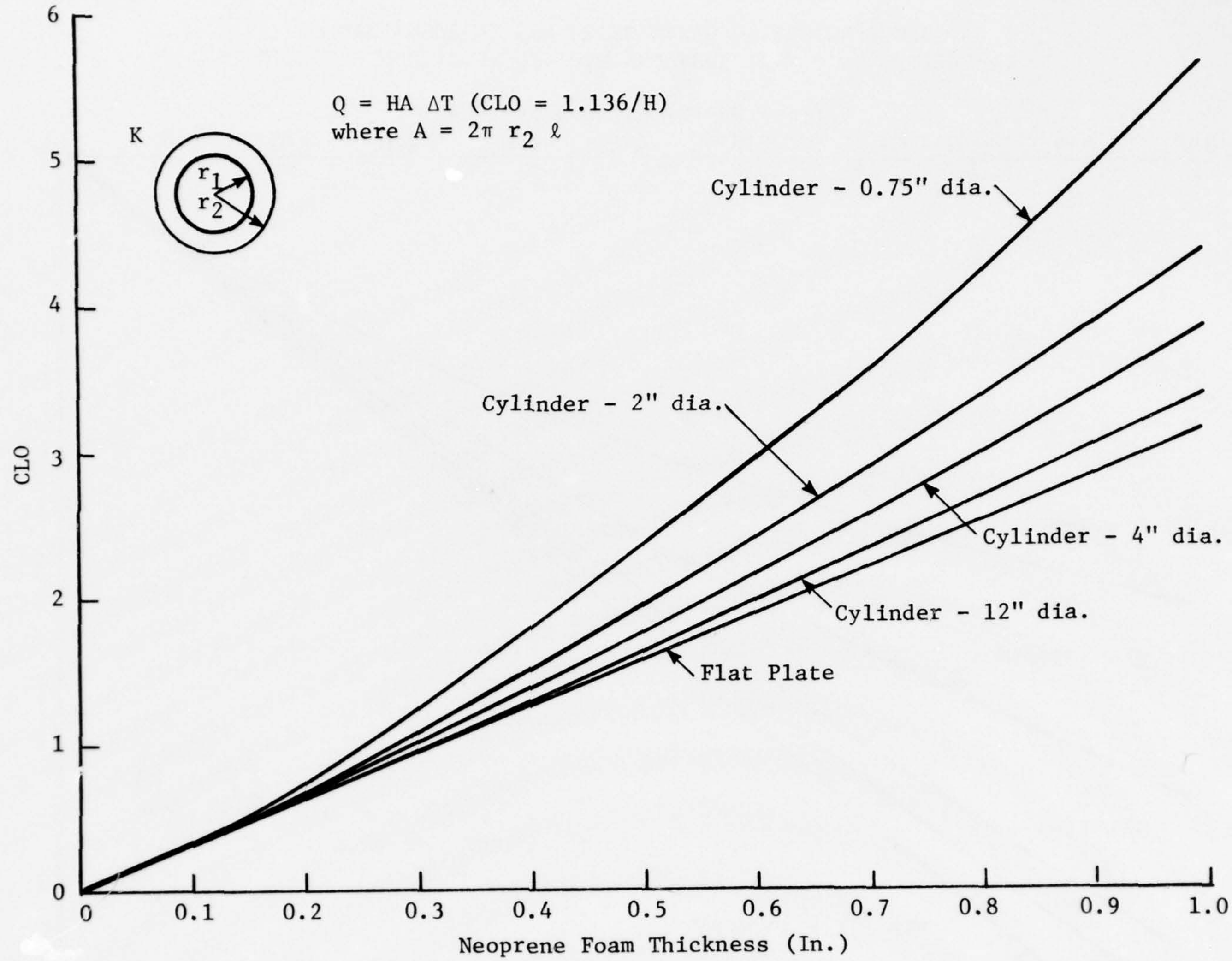

FIGURE 4. INSULATION OF FOAM NEOPRENE (K = 0.03 B/FT-HR-F) ON CYLINDERS AT SEA LEVEL BASED ON OUTSIDE RADIUS

By looking at the thickness component of a diver's suit in such a manner, the thermal behavior of an unlimited variety of suit designs can be predicted by knowing the thermal behavior of flattened simulations of each component. Additionally, the effects of depth, current speed, gas variations, thickness, etc., on the thermal behavior of diver's suits can be predicted by observing their effects on individual suit components. The following text examines the effects of each of these parameters on R_{og}, R_{uw}, R_L, and R_F. Where possible, experimental data was used to verify the behavior of these suit components. Finally, the thermal behavior of suit composites were predicted and compared with data obtained from copper manikin testing.

FILM INSULATION, R_F

The suit film insulation, the reciprocal of its heat transfer film coefficient, h_c, was shown to be approximated to acceptable accuracy by assuming that the human body is represented as a summation of cylinders[1]. For liquids flowing over a single cylinder, McAdams[2] showed empirically that the average film coefficient of that cylinder can be calculated using the equation

$$\bar{h}_c = (0.35 + 0.56\ Re_d^{0.5})\ Pr_f^{0.31} K_f/D$$

or

$$Clo_F = 1.136/\bar{h}_c = 1.136/(0.35 + 0.56\ Re_d^{0.5})\ Pr_f^{0.31} K_f/D \qquad (4)$$

where:

Re_d = Reynolds number = $\frac{\rho VD}{\mu}$

ρ = density of fluid, lb/ft^3

V = fluid velocity, ft/sec

D = cylinder diameter, ft

μ = fluid viscosity, lb/ft-sec

Pr_f = fluid Prandtl number

K_f = fluid thermal conductivity, Btu/hr-ft-^oF .

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[1] Witherspoon, et al., *Heat Transfer Coefficients of Humans in Cold Water,* from proceedings Symposium Internationale Thermal Regulation Comportementale Lyon, France, 7-11 September 1970.

[2] McAdams, W. H., *Heat Transmissions,* 3rd Ed., McGraw-Hill, New York.

When the fluid happens to be water, as in diving, only minor effects are seen in the average film coefficient over the range of pressures and temperatures normally encountered, because there are only small variations in the thermal properties. Thus, the cylinder diameter and fluid velocity are the major parameters of concern in this component of suit insulation. Figure 5 shows that, in the case of water flowing over cylinders approximating various segments of the human body, the insulation value of this film is quite small; in all cases less than 0.02 clo. However, prior to diver entry into the water, Figure 5 shows that the insulating value of this film can be quite significant in air. This is a good illustration that a waterproof suit which provides good passive insulation for temperature extremes in water requires a very different design from a suit for land use.

OUTER GARMENT INSULATION, R_{og}

The outer garments of most dry suits and all wet suits are fabricated from closed-cell, foamed rubber compounds. It is well known that the effectiveness of closed-cell foam to retain diver body heat diminishes rapidly as depth (pressure) increases. The effectiveness of any material as a thermal insulator is primarily dependent upon its ability to entrap gases. Thus, porous materials such as foamed rubber, with a high volume of entrapped air, serve as excellent insulators in an uncompressed state. Jacob[3] describes an expression derived by Maxwell for the apparent conductivity, K_a, of porous insulating materials, showing its dependency on the void fraction of the entrapped gas.

$$K_a = K_s \frac{1 - (1 - aK_p/K_s)b}{1 + (a - 1)b} \qquad (5)$$

where

$a = 3K_s/(2K_s + K_p)$

$b = V_p/(V_s + V_p)$ = void fraction

V_s = total solid volume

V_p = total entrapped gas volume

K_s = conductivity of solid

K_p = conductivity of entrapped gas .

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[3] Jacob, M., *Heat Transfer,* Vol. 1, p. 83, John Wiley, New York.

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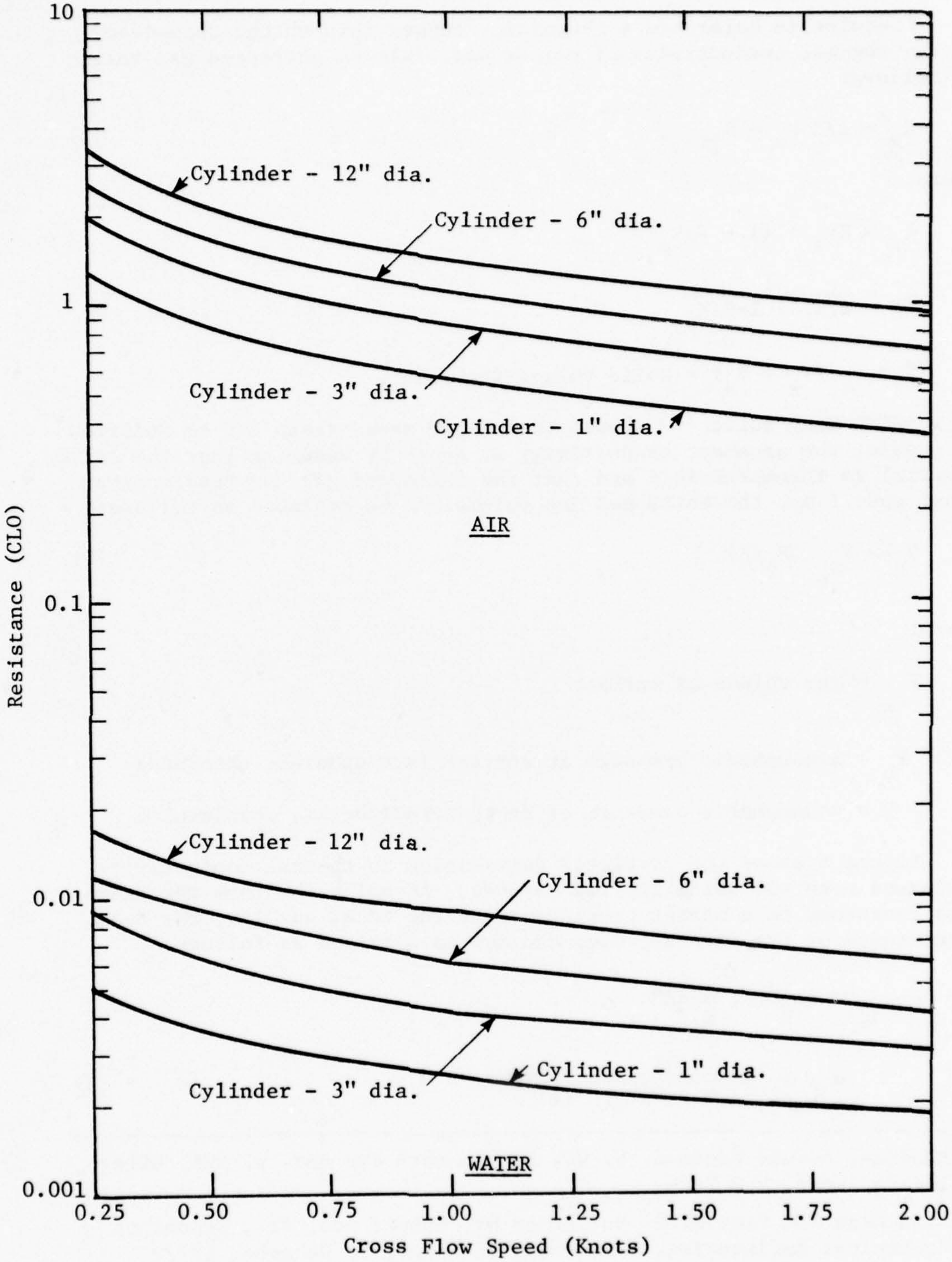

FIGURE 5. SURFACE RESISTANCE TO HEAT FLOW FROM CYLINDER IN WATER AND AIR

Likewise in Reference 4 Shumeister showed this strong dependency of the thermal conductivity of porous materials on entrapped gas volume as follows:

$$K_a = 1/3\ K_x + K_y \tag{6}$$

where

$$K_x = \emptyset K_s + (1 - \emptyset)K_p$$

$$K_y = \frac{1}{\emptyset/K_s + 1-\emptyset/K_p}$$

$$\emptyset = V_s/(V_p + V_s) = \text{solid volume fraction} .$$

In an NCSL Memo Butler[5] showed that these expressions can be modified to predict the apparent conductivity at depth by assuming that the solid material is incompressible and that the entrapped gas compresses as an ideal gas; i.e., the entrapped gas volume can be replaced as follows:

$$V_p = V_{p_o}\ (P_o/P) \tag{7}$$

where:

V_{p_o} = gas volume at surface

P_o = atmospheric pressure at surface (atmospheres, absolute)

P = atmospheric pressure at depth (atmospheres, absolute) .

Figure 6 shows the predicted degradation in thermal conductivity of foamed neoprene using the two methods. Assuming the foam thickness also decreases in a manner predictable by the ideal gas law, the foam conductance or its inverse, Clo, can now be obtained as follows:

$$Clo_{og} = \frac{1.136}{H} = \frac{1.136}{K_a/L}$$

$$= \frac{1.136}{K_a/L_o[1 + b(P/P_o - 1)]} \tag{8}$$

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[4] Penzias, W. and Goodman, M. W., *Man Beneath the Sea,* p. 608, Wiley-Interscience, New York.

[5] NCSL Code 751 Memo H. S. Butler to Dr. Robert Adt, Jr., School of Mechanical Engineering, University of Miami, 15 December 1972.

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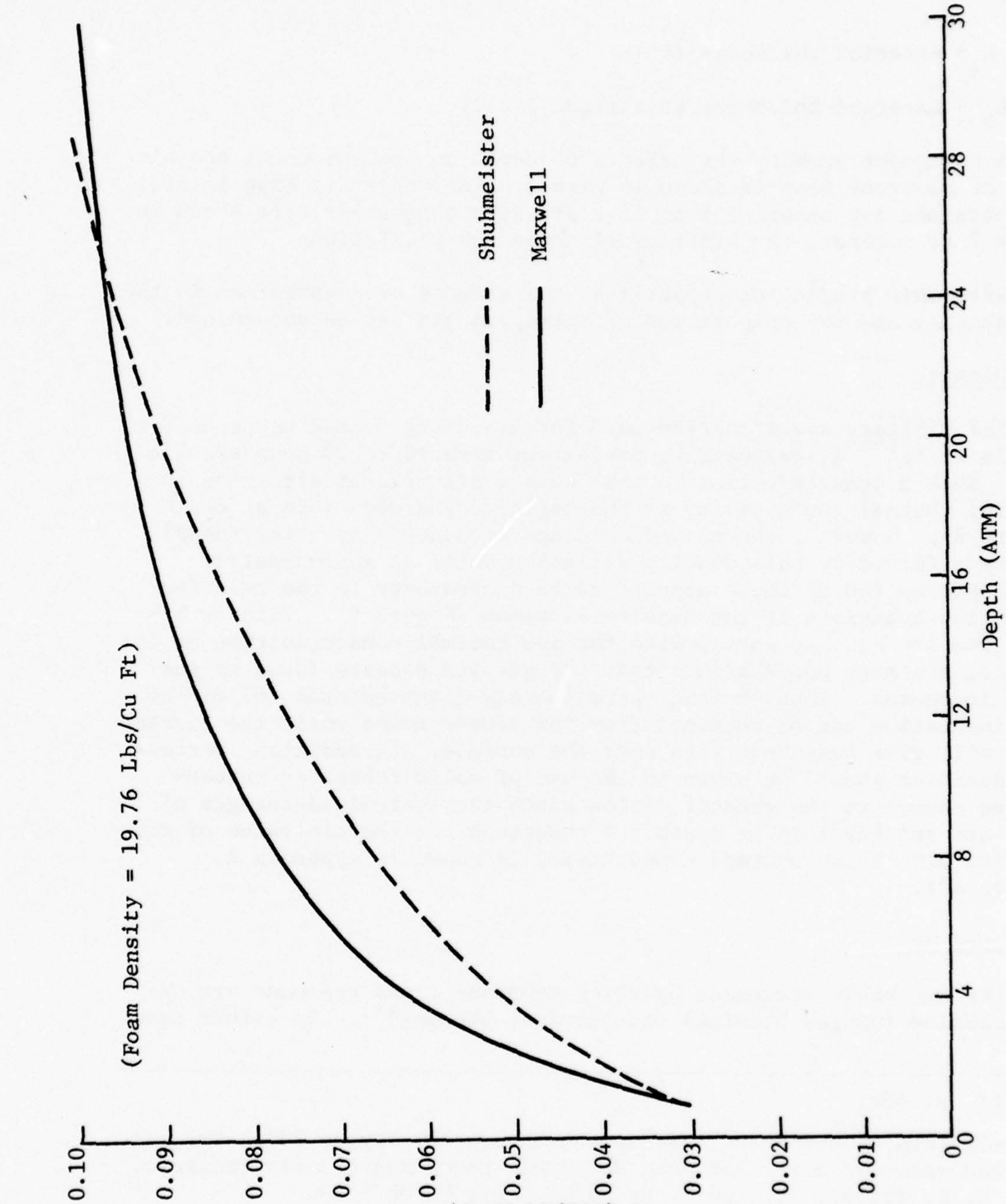

FIGURE 6. THERMAL CONDUCTIVITY OF FOAM NEOPRENE AT HYPERBARIC CONDITIONS

where:

L = material thickness (ft)

L_o = material thickness at surface (ft) .

A nomograph showing the effects of depth on the thickness and clo value of neoprene foam is shown in Figure A1 Appendix A. Experimental data obtained for neoprene foam in a pressure chamber[6], are shown in Figure 7 to indicate the accuracy of these two predictions.

With this prediction capability, the effects of a variation in the foam density and the composition of entrapped gas can be determined.

Foam Density

The military specification used for procuring foamed neoprene for diver's suits[7] allows density variations from 10 to 20 pounds/cubic foot. Such a density variation will have a significant effect on the material thermal conductivity at the surface, and even more at depth (Figure 8). However, thermal conductance (conductivity ÷ thickness) is less affected by this density variation until at approximately 7 atmospheres (60 m) there appears to be a crossover in the relative insulation behaviors of the density extremes (Figure 9). This is because the low density foams, with the low thermal conductivities at the surface, are more compressible than the greater density foams as the depth increases. Thus, beyond approximately 7 atmospheres (60 m) the best insulation can be obtained from the denser foams while the lighter foams will give less heat loss near the surface. In addition, serious consideration should be given to the use of solid rubber or rubber-covered canvas at the greater depths since the thermal advantages of foams are quickly lost at depth. A nomograph for the clo value of any material with known thermal conductivity is shown in Appendix A (Figure A2).

Entrapped Gas

The two basic processes by which neoprene foams are made are direct gassing (or gas blowing) and chemical blowing[4]. In either case,

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[4] ibid, p. 601.

[6] Naval Ship Research and Development Laboratory Report 2903, *Thermal Conductance of Diver Wet Suit Materials Under Hydrostatic Pressure,* by H. S. Butler, Jr. and R. H. Payne, Jr., March 1969.

[7] MIL-W-82400, *Wet Suits, Neoprene,* 22 October 1965.

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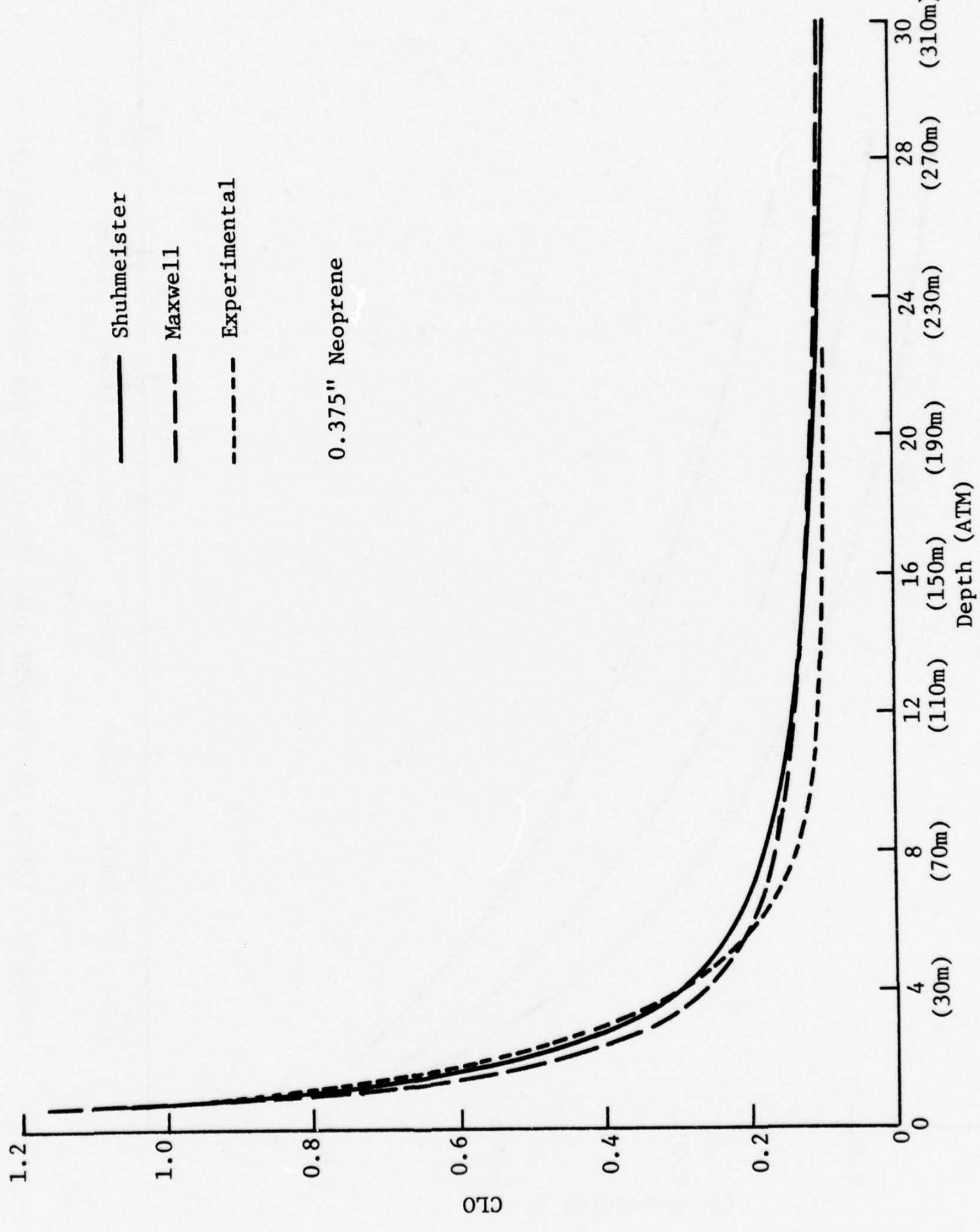

FIGURE 7. INSULATION VALUES OF FOAM NEOPRENE AT HYPERBARIC CONDITIONS

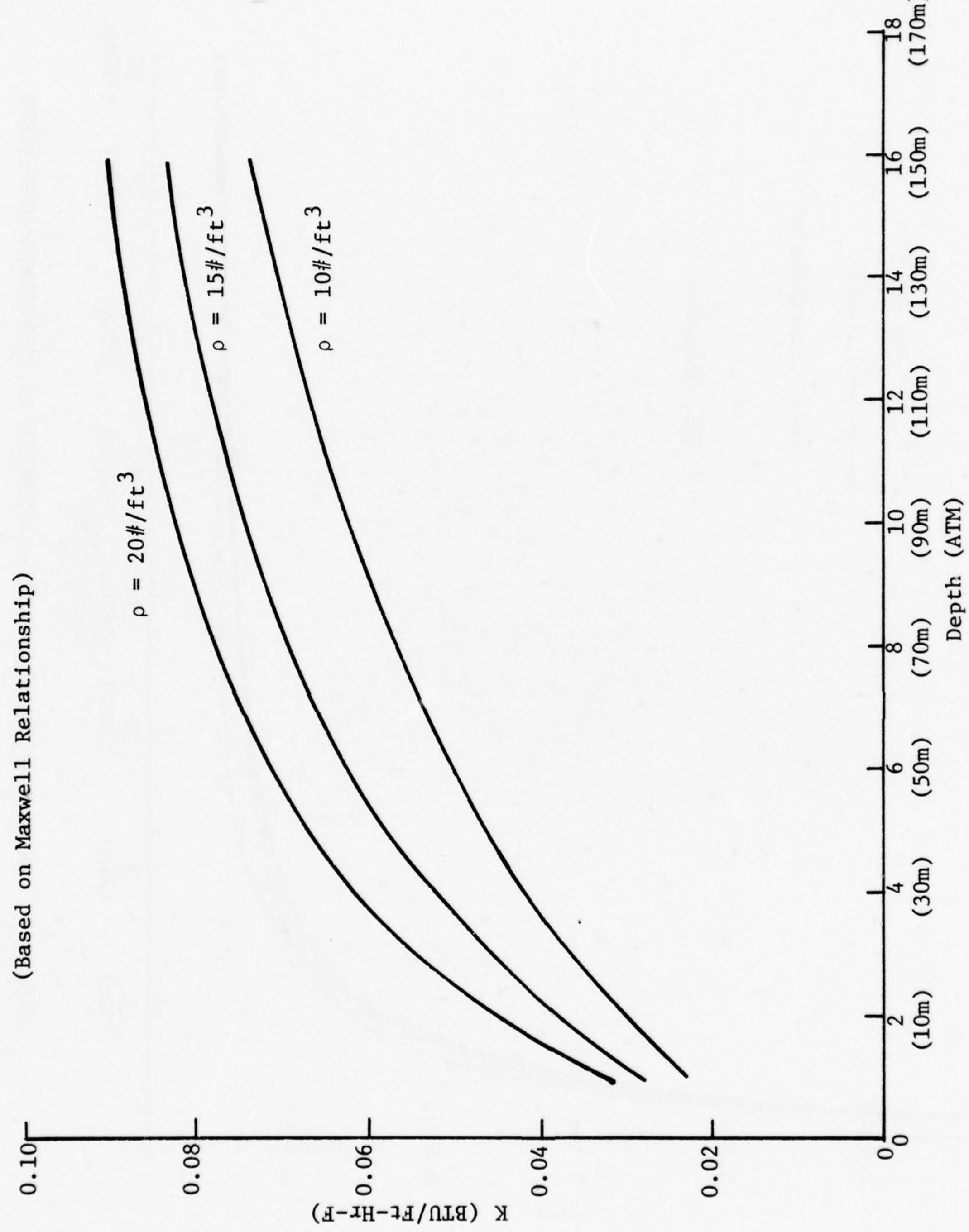

FIGURE 8. EFFECT OF NEOPRENE FOAM DENSITY ON ITS THERMAL CONDUCTIVITY AT HYPERBARIC CONDITIONS

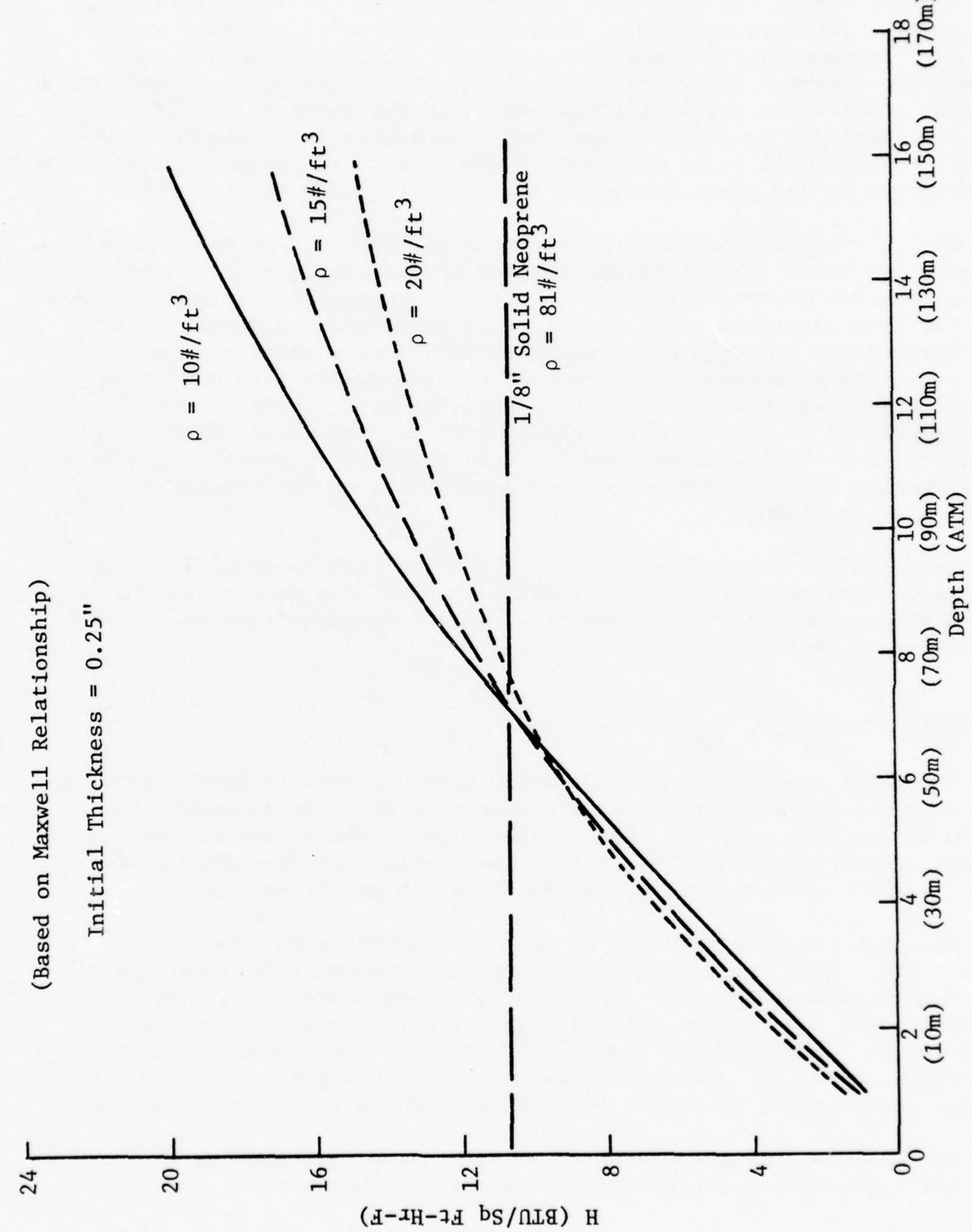

FIGURE 9. EFFECT OF NEOPRENE FOAM DENSITY ON ITS THERMAL CONDUCTANCES AT HYPERBARIC CONDITIONS

nitrogen gas causes the expansion and formation of the foam cellular structure. Like most materials, neoprene is permeable to gases and liquids. In atmospheres other than nitrogen, diffusion takes place through the neoprene at a rate proportional to the gas partial pressure gradient that exists across the material. At the surface, in air, the foam soon comes to equilibrium with air. In other gas or liquid environments, the foam will reach equilibrium with that environment at a rate proportional to the permeability of that gas or liquid to neoprene.

This diffusion process is accelerated at depth due to the increased pressure gradient. This behavior is most noticeable in a diving bell or habitat where high concentrations of helium are present. Helium diffuses into the foam structure until the foam has re-expanded and equilibrium with the ambient atmosphere is reached. Reference 4 shows experimental evidence of this behavior. The thermal effects due to this diffusion process are shown in Figure 10. Note that the major influence of the gas composition is seen at the surface where the gas volume fraction is greatest. Here helium is not likely to be a problem since air or oxygen would usually be the major atmosphere constituent of the habitat or bell at the shallow depths.

In a similar manner, seawater will diffuse into neoprene foam during prolonged exposures. Should water saturation or even partial saturation of the foam occur, the insulation value of the neoprene foam garment will be severely jeopardized.

UNDERWEAR INSULATION, R_{uw}

Following outer garment compression of a dry suit at depth, or with the use of rubberized canvas outer garments, a diver is dependent primarily on his underwear for thermal protection. The efficiency of his underwear to retain body heat in cold environments is also dependent upon its ability to entrap and retain gases, in particular air.

Heat has three major modes of transfer through underwear (Figure 11). Heat is transferred through the underwear material fibers at a rate dependent upon the fiber thermal conductance. Secondly, heat is transferred through the entrapped gas at a relatively slower rate because most gases are poor thermal conductors. And finally, heat is transferred by way of either natural convective currents within the entrapped gas pockets, or forced convective currents through the underwear.

An ideal underwear would be composed of small gas pockets to minimize both natural and forced convective currents between the diver's

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(4) ibid, p. 607.

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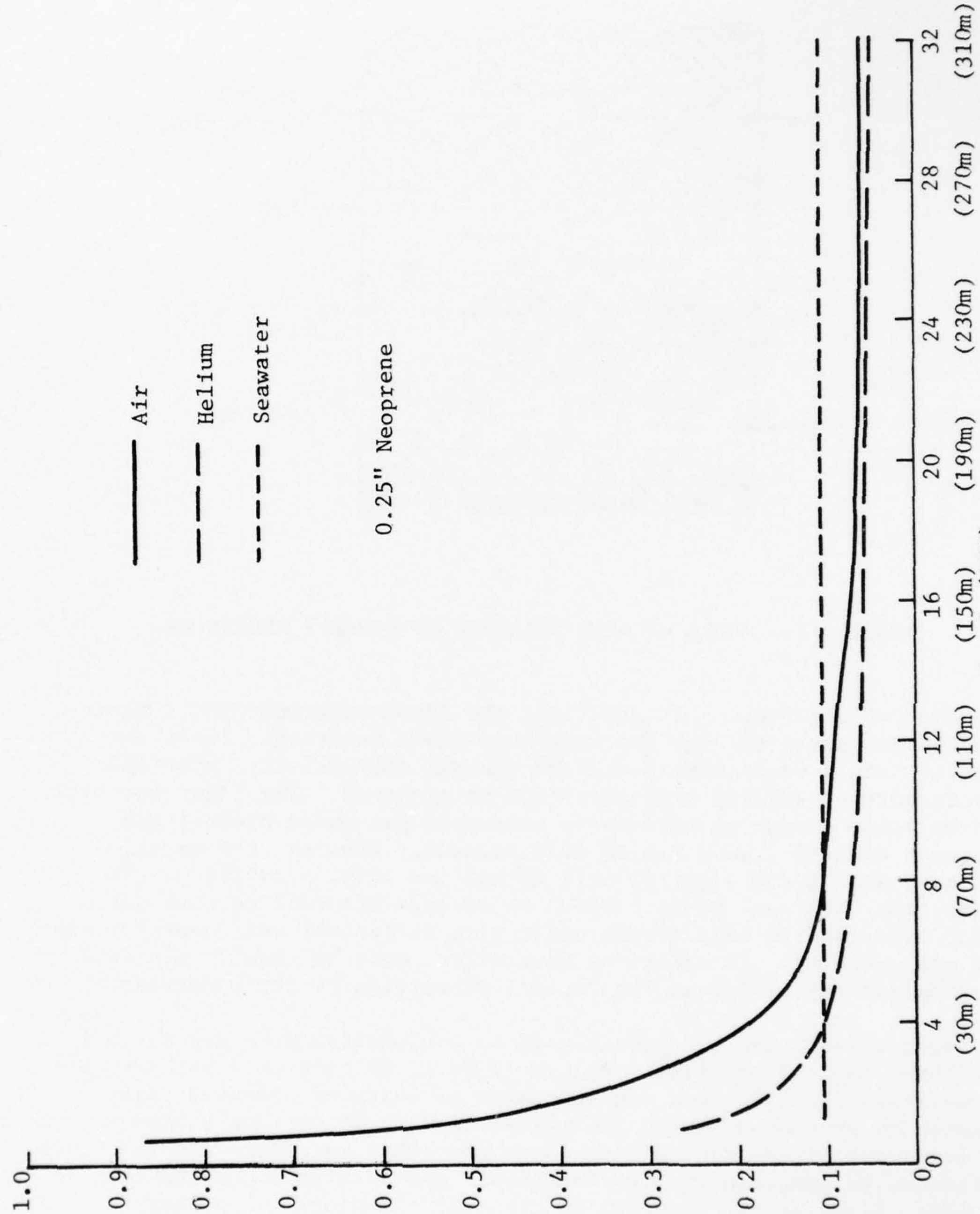

FIGURE 10. INSULATION VALUES OF FOAM NEOPRENE SATURATED WITH VARIOUS MATERIALS

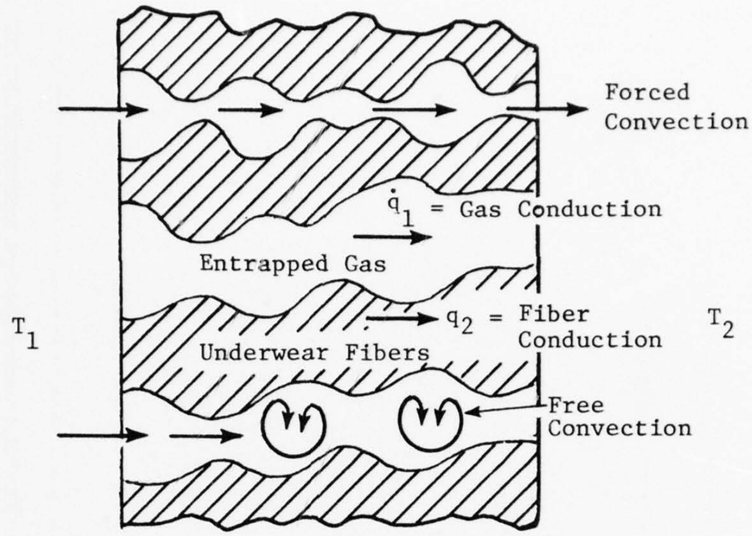

FIGURE 11. MODES OF HEAT TRANSFER IN DIVER'S UNDERWEAR

body and outer garment. In addition, the ideal underwear would minimize thermal paths through the underwear fiber material. The fiber material itself would have a minimum thermal conductivity, provided satisfactory structural properties can be achieved. The fiber material must be stiff enough to retain the entrapped gas under hydrostatic pressures of 1 to 2 psig due to suit squeeze. However, the material stiffness should not significantly affect the diver's mobility. In effect, the underwear would furnish an optimum tradeoff between gas pocket size for low heat transmission with sufficient stiffness for support and mobility. In addition, some effort must be made to minimize sweating and its effect on the thermal properties of the underwear.

Most conventional underwear used in conjunction with dry suits fall into three major catetories: open cell foam, nylon pile, and Navy cotton waffle. The thickness and/or number of suits of underwear are selected to provide adequate thermal protection in various environments. The main problem associated with these underwear materials are their low resistance to compression from even small hydrostatic pressures (Figure 12). Although the majority of dry suit interiors are pressure equalized with ambient conditions by way of a diver's respiratory gas, there still exists a hydrostatic pressure variation between the diver's

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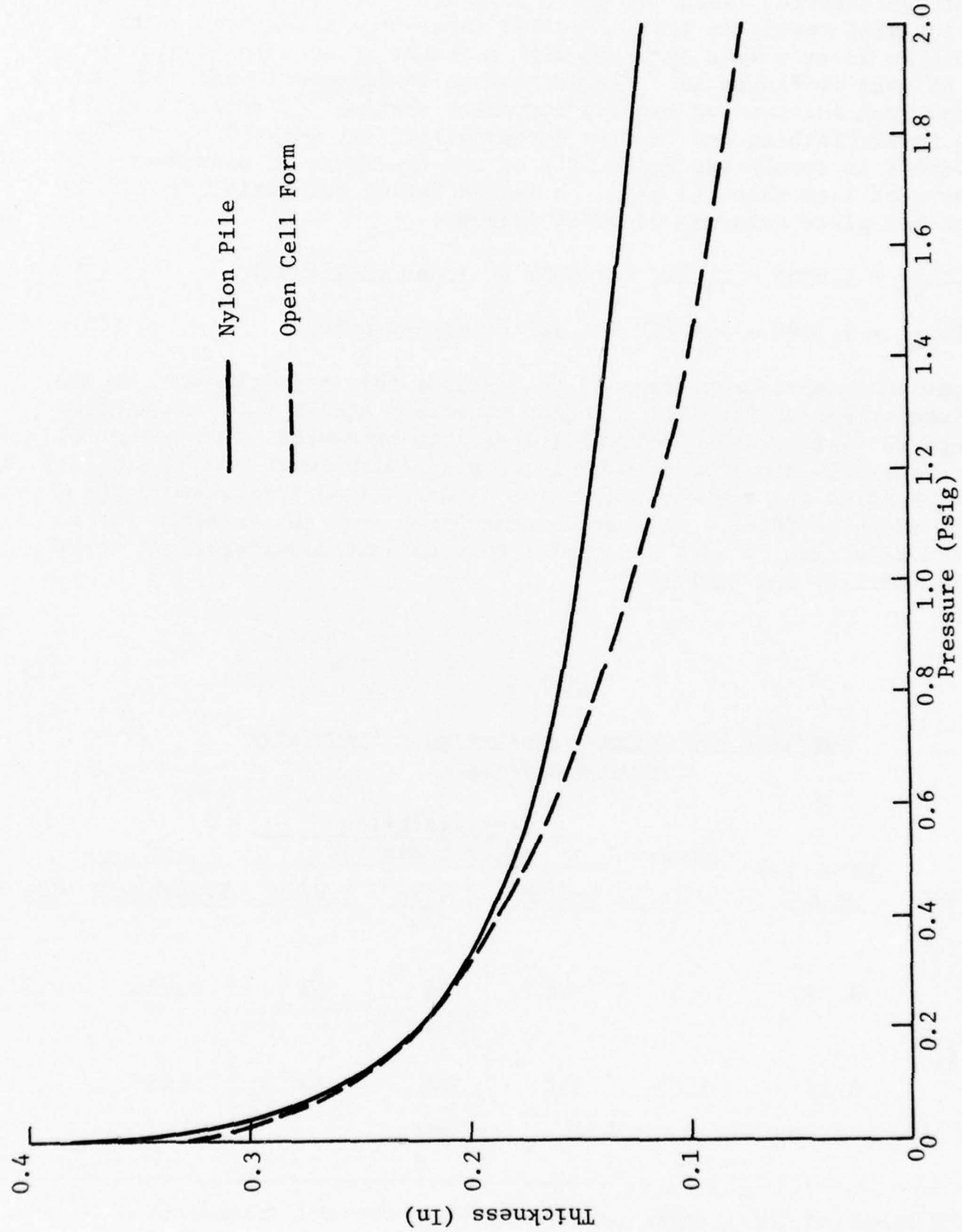

FIGURE 12. THICKNESS OF DIVER'S UNDERWEAR UNDER VARIOUS HYDROSTATIC PRESSURES

chest and feet of approximately 2 psig due to the higher ambient water pressure at the feet (with the diver in erect position). This pressure variation will result in less effective insulation thickness in the area of the diver's feet and legs with a resulting loss in insulative value as seen in Figure 13. The data shown in Figures 12 and 13 were obtained from Instron and guarded hot plate testing[8], respectively, at the Naval Clothing and Textile Research Facility (NCTRF). Note the rapid decay in insulative capability of the two types of underwear with a squeeze of less than 0.5 psig. A second degree polonomial fit to the guarded hot plate data was found as follows:

$$Clo_{uw} = 1.6554 - 2.798P + 1.6537\ P^2 \text{ (open cell foam)} \qquad (9)$$

$$Clo_{uw} = 1.2768 - 1.9381P + 1.102\ P^2 \text{ (nylon pile)} \qquad (10)$$

Two approaches have been proposed to overcome this reduction in leg and feet insulation. First, stiff spacer materials can be used in the feet and legs to resist the squeeze of hydrostatic pressures. Two potential spacer materials are listed in Table 1, along with their compressibility characteristics and thermal properties as determined from guarded hot plate testing at NCTRF. It must be remembered that the criteria for the ultimate selection of such a material must include considerations for the diver's mobility and comfort.

TABLE 1*

PHYSICAL AND THERMAL PROPERTIES OF CANDIDATE SPACER MATERIALS

Materials	Thickness (in.)	Density $\#/ft^3$	Compressibility After 5 Minutes $1\ \#/in^2$	$2\ \#/in^2$	$3\ \#/in^3$	K $B/ft\text{-}hr\text{-}^oF$	Clo
Uniroyal Trilok 6027	0.208	3.5	4%	6%	8%	0.054	0.37
Uniroyal Trilok 6028	0.295	5.67	25%	34%	46%	0.069	0.41

*Data obtained from Uniroyal sales literature.

(8) ASTM Standard C177, *Tests for Steady State Thermal Transmission Properties by Means of Guarded Hot Plate.*

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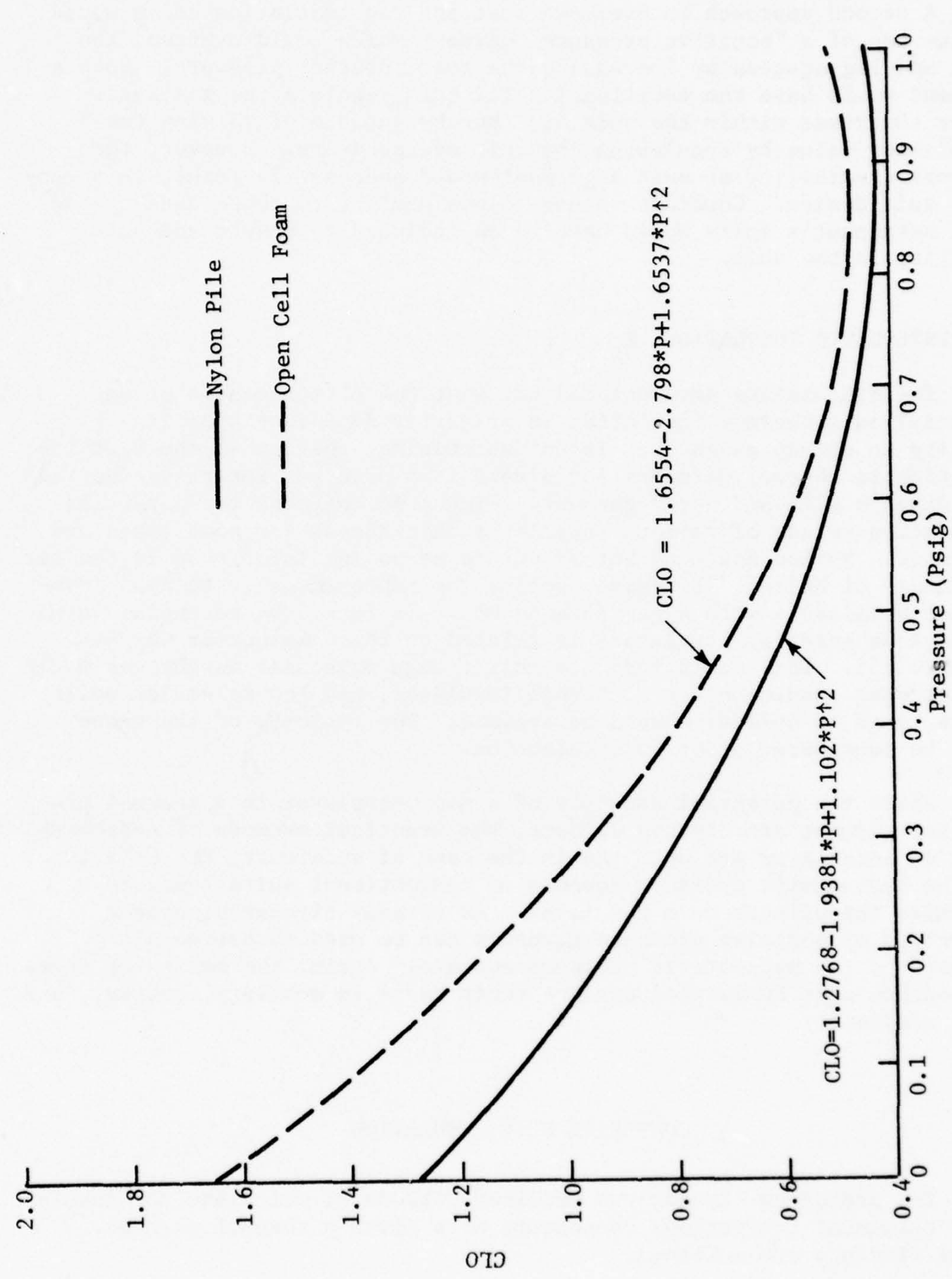

FIGURE 13. INSULATIVE VALUE OF DIVER'S UNDERWEAR UNDER VARIOUS HYDROSTATIC PRESSURES

A second approach to overcome feet and leg insulation decay would be the use of a "positive pressure" garment which could overcome the foot and leg squeeze by increasing the suit interior pressure. Such a garment would have the additional ability to regulate the gas interlayer thickness within the suit and thereby capable of varying the insulation value by regulating the suit overpressure. However, the thermal flexibility of such a garment would necessarily result in a complex suit design. Constant volume joints similar to those used by the NASA astronaut's suits would have to be included to ensure adequate mobility in the suit.

GAS INTERLAYER INSULATION, R_L

The discussions have pointed out that the effectiveness of any material as a thermal insulation is primarily dependent upon its ability to entrap gases. It is not surprising, then, that the best insulation in thermal garments for divers is a pure gas interlayer between the diver's skin and outer garment. Figure 14 compares the potential insulation values of various interlayer thicknesses for some gases and seawater. Notice how much better air is as an insulator than is the same thickness of helium. Likewise, notice the improvement in thermal insulation obtainable with a gas such as CO_2. In fact, the potential value of various gases as insulators is related to their molecular weights (Figure 15). This would indicate that a high molecular weight gas would be the best candidate for a thermal insulator, and low molecular weight gases, such as helium, should be avoided. The toxicity of the gases must be considered prior to a selection.

While the potential benefits of a gas interlayer in a thermal protection garment are clearly evident, the practical methods of achieving such an interlayer are not. As in the case of underwear, the effects of the hydrostatic pressure squeeze on conventional suits tends to minimize the effects of a gas layer. As already discussed, spacer materials of positive pressure garments can be used to overcome the effects of the hydrostatic pressure squeeze. Again, the merits of these approaches must be weighed against their costs in mobility, comfort, and suit complexity.

COMPOSITE SUIT INSULATION

The preceding discussions outlined methods to calculate the insulation values of the various components of a diver's thermal garment. These findings are outlined.

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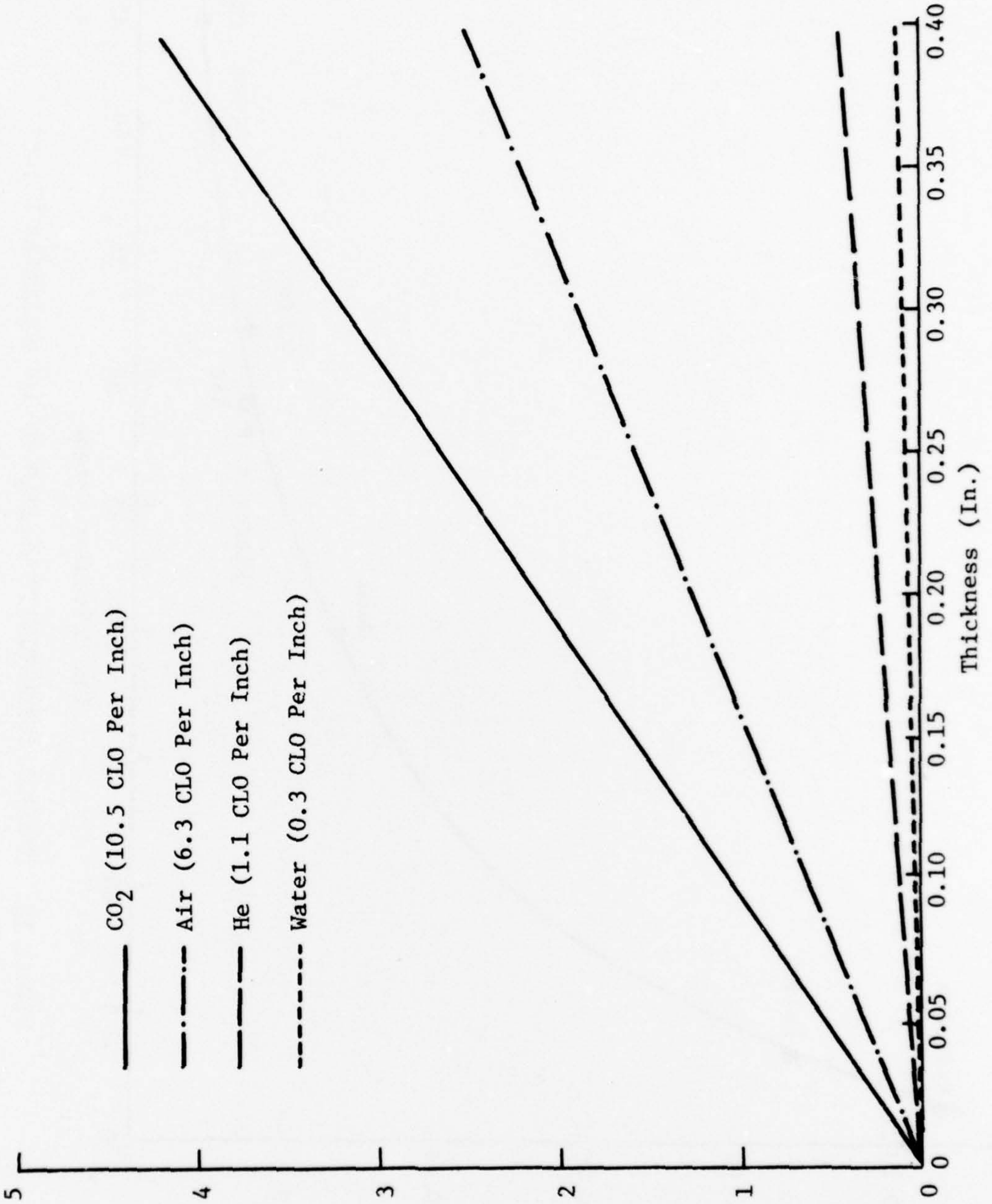

FIGURE 14. INSULATION VALUES OF VARIOUS MATERIALS IN PURE CONDUCTION

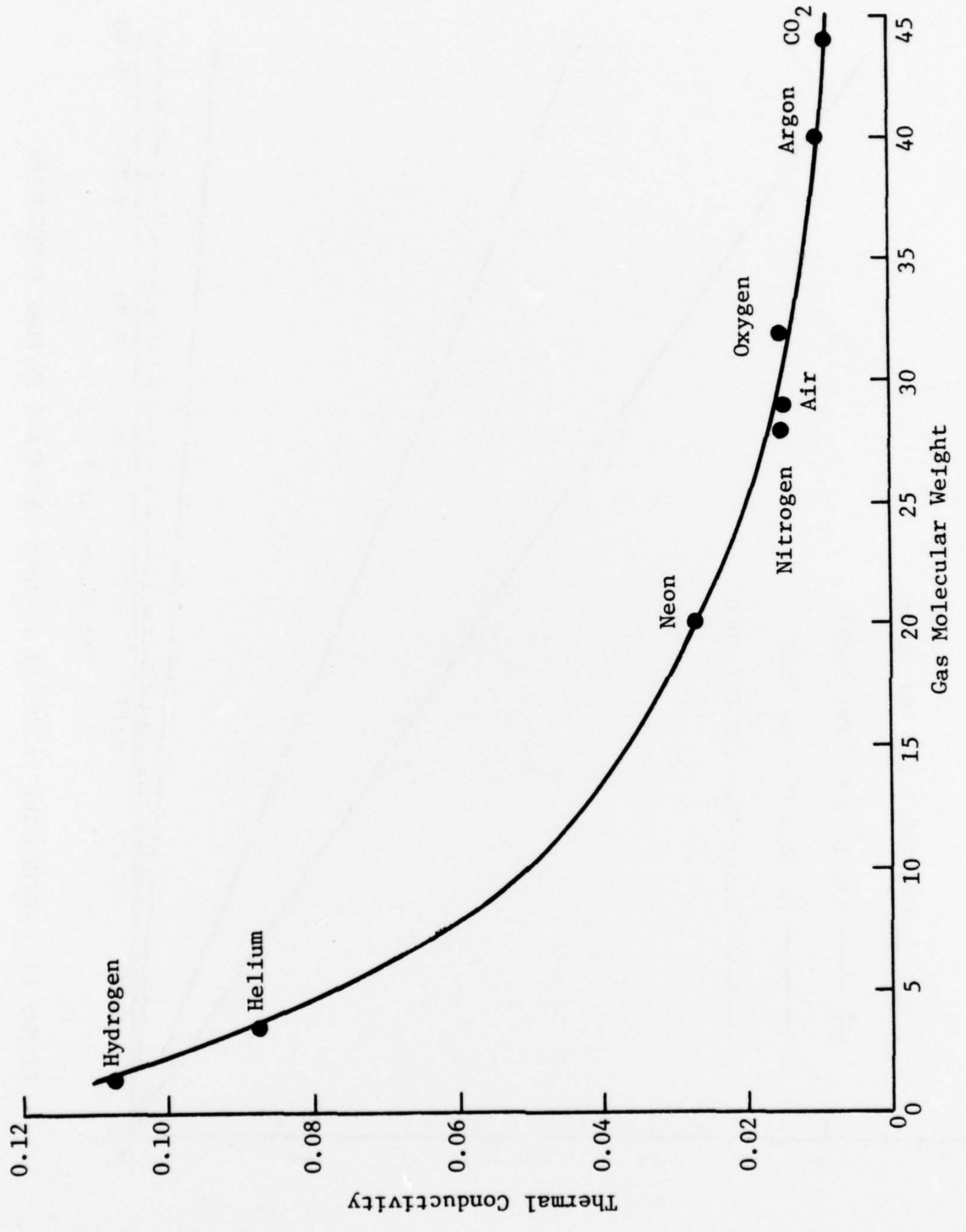

FIGURE 15. THERMAL CONDUCTIVITY RELATED TO GAS MOLECULAR WEIGHT

INSULATION FILM BETWEEN DIVER SUIT AND SURROUNDINGS

$$Clo_F = 1.136/(0.35 + 0.56\ Re_d)\ Pr_f^{0.31} K_f/D \qquad (4)$$

This relationship is a function of the free stream fluid (seawater) properties, body diameter, and flow rate. There is little effect as depth varies.

INSULATION DUE TO DIVER'S OUTER GARMENT

Foam Neoprenes

$$Clo_{og} = 1.136/[K_a/L_o(1 + b(P/P_o-1))] \qquad (8)$$

where K_a is obtained from either the Maxwell relationship in Equation (5) and Equation (7), or the Shuhmeister relationship in Equation (6) and Equation (7). Both of these relationships show a strong dependency on depth and thickness, as well as the material properties of the outer garment.

Solid or Rubber Covered Canvas

$$Clo_{og} = 1.136/(K_a/L_o) \qquad (1)$$

This relationship is not depth dependent, and garments made from this material should see little change in thermal properties with depth changes.

INSULATION DUE TO DIVER's UNDERWEAR

Open Cell Foam

$$Clo_{uw} = 1.6554 - 2.798\ P + 1.6537P^2;\ P \leq 1\ \text{psi} \qquad (9)$$

Nylon Pile

$$Clo_{uw} = 1.2768 - 1.9381\ P + 1.102P^2;\ P \leq 1\ \text{psi} \qquad (10)$$

These empirically derived relationships for two types of underwear vary in insulative value with the hydrostatic pressure gradient between the diver's feet and legs to his chest. Other underwear and underwear combinations are shown in Table 2, along with their insulative values at the surface. Some experimental work will be required to determine the insulation degradation with depth.

(Text Continued on Page 29)

TABLE 2

INSULATION VALUES OF VARIOUS GARMENT AND UNDERWEAR COMBINATIONS

(From NCTRF Guarded Hot Plate Testing)

Test Assembly*	Assembly Thickness (in.)	Clo Value	K (B/ft-hr-F)
5	0.295	0.97	0.029
5-30	0.398	1.31	0.029
5-20-30	0.67	1.92	0.033
5-21-30	0.60	1.98	0.029
30-30	0.21	0.71	0.028
20	0.295	0.41	0.069
21	0.208	0.37	0.054
5-1-30	0.525	1.67	0.030
1-5-20-30	0.795	2.33	0.032
1-5-21-30	0.730	2.34	0.30

*Code	Description
1	1/8-inch polyethylene vinyl acetate foam (closed cell)
5	1/4-inch neoprene foam (closed cell)
20	Uniroyal Trilok No. 6028
21	Uniroyal Trilok No. 6027
30	Navy diver's waffle weave underwear

INSULATION DUE TO GAS OR FLUID INTERLAYER

The insulation values reported for the various gases and seawater in Figure 14 are based on the following simple relationship

$$Clo_L = 1.136/(K/L) \tag{12}$$

where

K = gas or liquid thermal conductivity

L = interlayer thickness .

This relationship is not depth dependent provided the interlayer gas composition remains the same.

PREDICTIONS OF GARMENT THERMAL BEHAVIOR

The relationships established for the various components of wet and dry suits can be used to predict the insulation values of sample composite suits using a slight modification of Equation (2).

$$Clo_{suit} = Clo_{og} + Clo_{uw} + Clo_L + Clo_f \quad .$$

The overall suit heat loss can likewise be predicted using the relationship of Equation (1).

$$\dot{Q} = HA(T_s - T_\infty) = \frac{1.136}{Clo} A(T_s - T_\infty) \quad .$$

Due to the flat plate analysis used in deriving the suit component relationships, care should be taken to use the log mean area, $\bar{A}$, in the above equation.

$$\bar{A} = \frac{2\pi(r_2 - r_1)\ell}{\ln(r_2/r_1)} \tag{3}$$

Figures 16 and 17 show the predicted thermal insulations calculated for sample dry and wet suits using the above analysis. These results were compared with experimental copper manikin test data at depths of about 3 feet[9] obtained for suits having similar features. Note the

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[9] Army Research Institute of Environmental Medicine, Natick, Mass.

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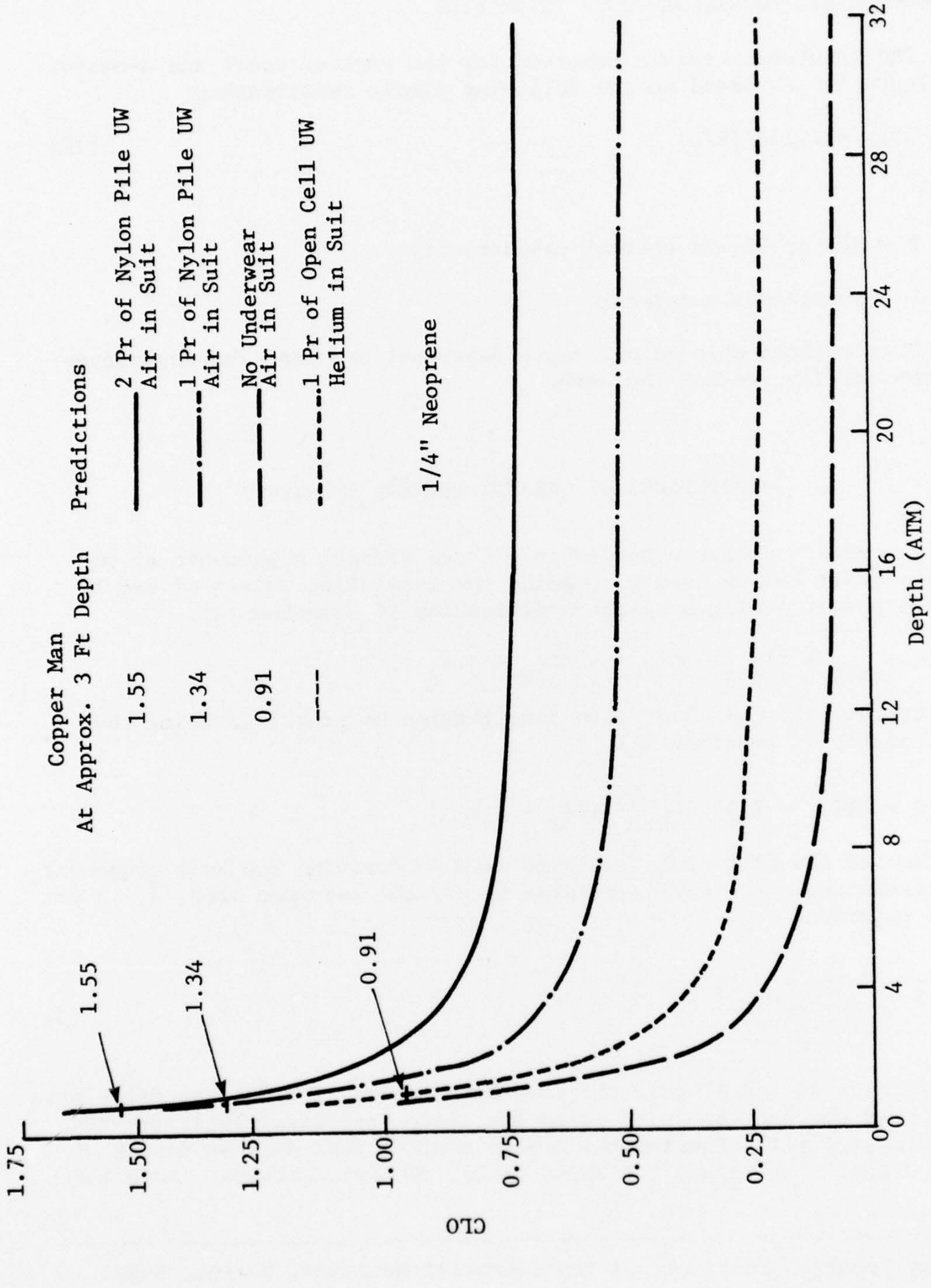

FIGURE 16. PREDICTIONS OF THE INSULATION VALUES OF NEOPRENE FOAM DRY SUITS WITH VARIOUS PAIRS OF UNDERWEAR

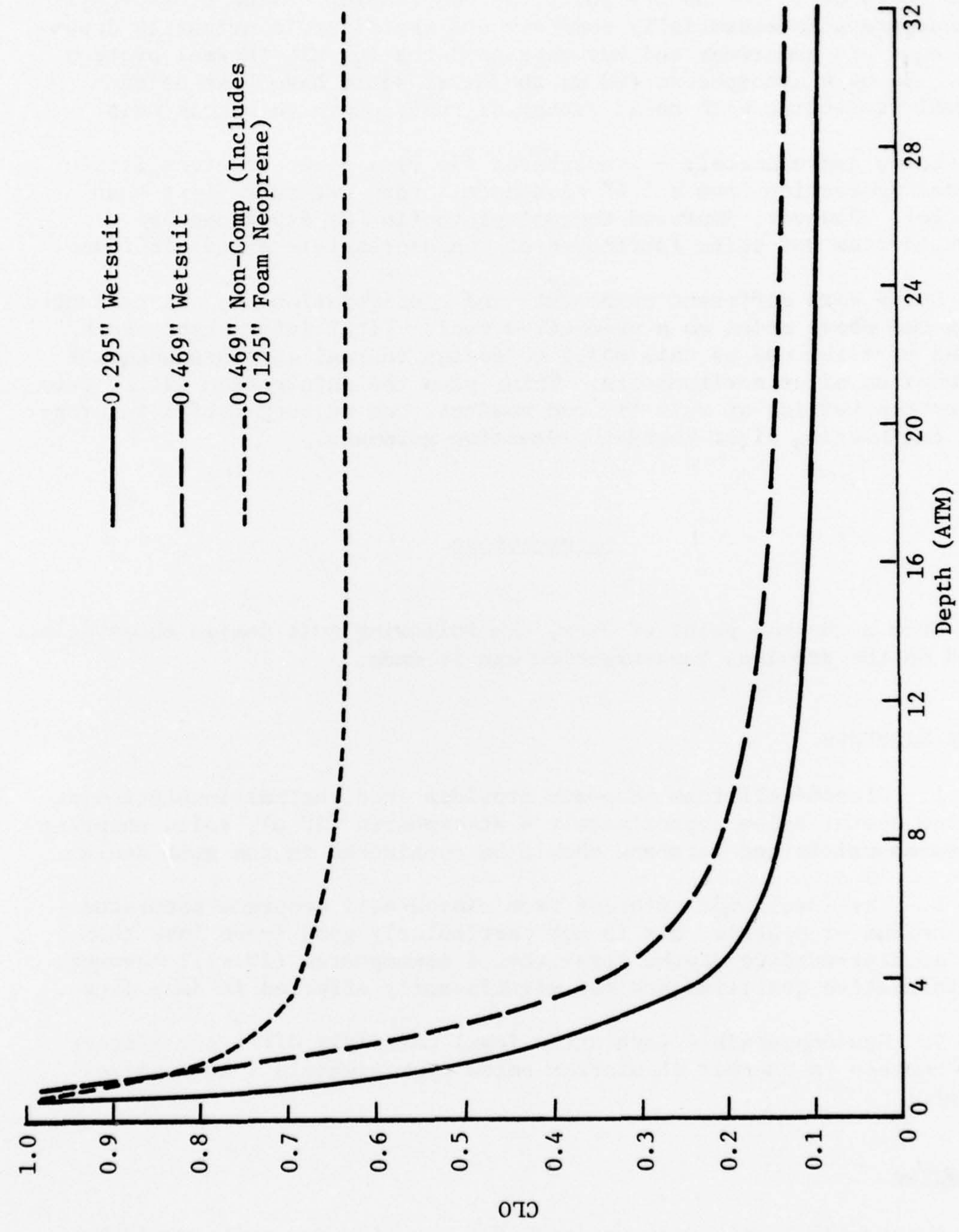

FIGURE 17. INSULATION VALUES OF WETSUITS AT HYPERBARIC CONDITIONS

rapid drop-off in clo value in the first 4 atmospheres of compression. Beyond this depth in the dry suit, the compression of the closed-cell from neoprene is essentially complete and the diver is primarily dependent upon his underwear and any entrapped gas for his thermal protection. Below 4 atmospheres (30 m) the diver would have just as much thermal protection with solid rubber or rubber-covered canvas suit.

Below approximately 4 atmospheres (30 m) a diver receives little thermal protection from a 1/4" closed-cell foam wet suit (less than 0.2 clo). However, improved thermal protection at depth can be expected from wet suits fabricated of noncompressible syntactic foams.

Suits with different components and configurations can be evaluated using the above model as a predictive tool. Vital information can be gained from the use of this model to design thermal garments adequate for various diver environments. This, plus the information gained from subjective testing of suit fit and comfort, can be very useful in properly engineering diver thermal protection garments.

OBSERVATIONS

From a thermal point of view, the following suit design observations based on the previous investigation can be made.

OUTER GARMENTS

1. Closed-cell foam neoprene provides good thermal insulation at shallow depth; below approximately 4 atmospheres (30 m), solid neoprene or canvas reinforced neoprene should be considered in the suit design.

2. The insulation afforded from closed-cell neoprene saturated with helium or a heliox mix is not particularly good (much less than air) at near-surface depths (less than 4 atmospheres (30 m)); however, its insulative qualities are not significantly affected in deep dives.

3. Noncompressible (syntactic foam) materials offer significant improvements in thermal insulation below approximately 4 atmospheres (30 m).

UNDERWEAR

1. An ideal underwear material for use with dry suits would be fabricated of a material containing many small gas pockets to minimize

both natural and forced convective currents between the diver's body and his outer garment.

2. Improved thermal properties can be obtained from underwear materials which are stiff enough to retain the entrapped gases in the underwear while under 1 to 2 psig hydrostatic pressures. (This stiffness behavior must be weighed against its effects on a diver's comfort and mobility.)

GAS INTERLAYERS

1. The greatest improvement and best control obtainable for diver's thermal insulation can be realized by the regulation of the gas interlayer between the diver's body and dry suit outer garment.

2. Low conductivity gases such as air or carbon dioxide are better insulators than helium or seawater (wet suits).

FILM COEFFICIENT

1. The water current speed has a negligible effect on the insulation qualities of a good wet or dry suit.

2. The insulation properties of a diver's suit in water is substantially different from its insulation value in air.

RECOMMENDATIONS

The use of noncompressible or canvas reinforced garments should be considered for deep dive applications. Such garments, when used in conjunction with appropriate underwear, would give maximum passive insulation at depth while minimizing the suit buoyancy variations during the dive. In addition, these garments would make the most efficient use of active heating systems in a diver's suit by minimizing the heat loss to the surroundings.

The use of closed-cell foam garments should only be considered in near-surface (less than 30 m) applications or when sufficient underwear is worn to offset the thermal collapse of the foam with depth. The use of the foam outer garment for deep dive applications would require a thick bulky suit to equal the same thermal insulation of a thin canvas-covered neoprene suit.

A material study should be initiated to investigate the design and construction of good thermal underwear for use with dry suits. Such a study should include the effects of foam density, pore size, and compressibility on the thermal behavior of the underwear at depth.

An investigation should be made of the use of positive pressure dry suits. Tradeoffs of the cost of construction of complex suits with their benefits in diver thermal protection must be made to evaluate their potential value in future diver garment designs.

Finally, the feasibility of insulating a diver's body, or parts of his body (extremities), with low conductivity gases should be investigated as a supplement to the positive pressure garment, or garment accessories (gloves or boots).

APPENDIX A

INSULATION NOMOGRAPHS

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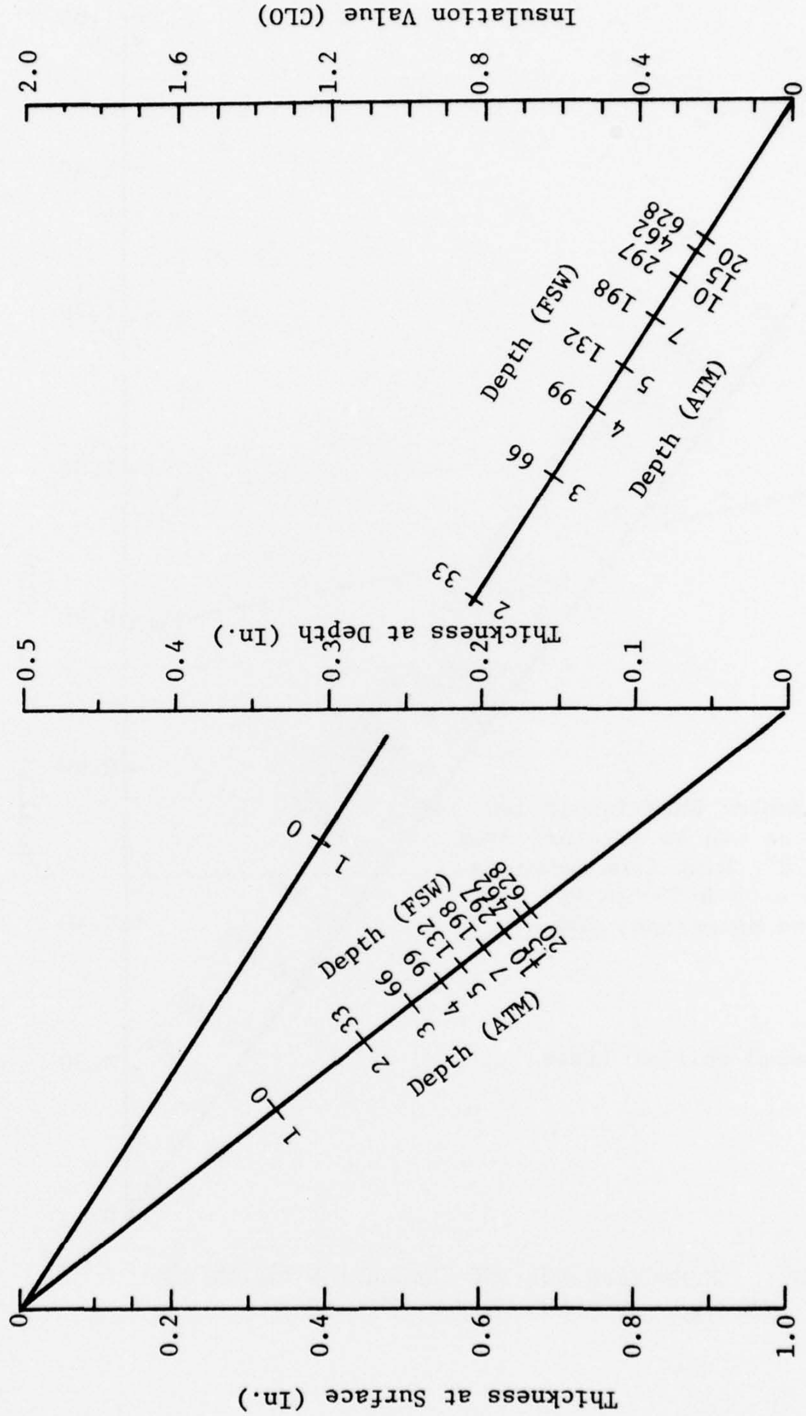

FIGURE A1. NOMOGRAPH FOR THE THICKNESS AND INSULATION VALUE OF NEOPRENE FOAM AT DEPTH (K = 0.03 B/ft-hr-°F)

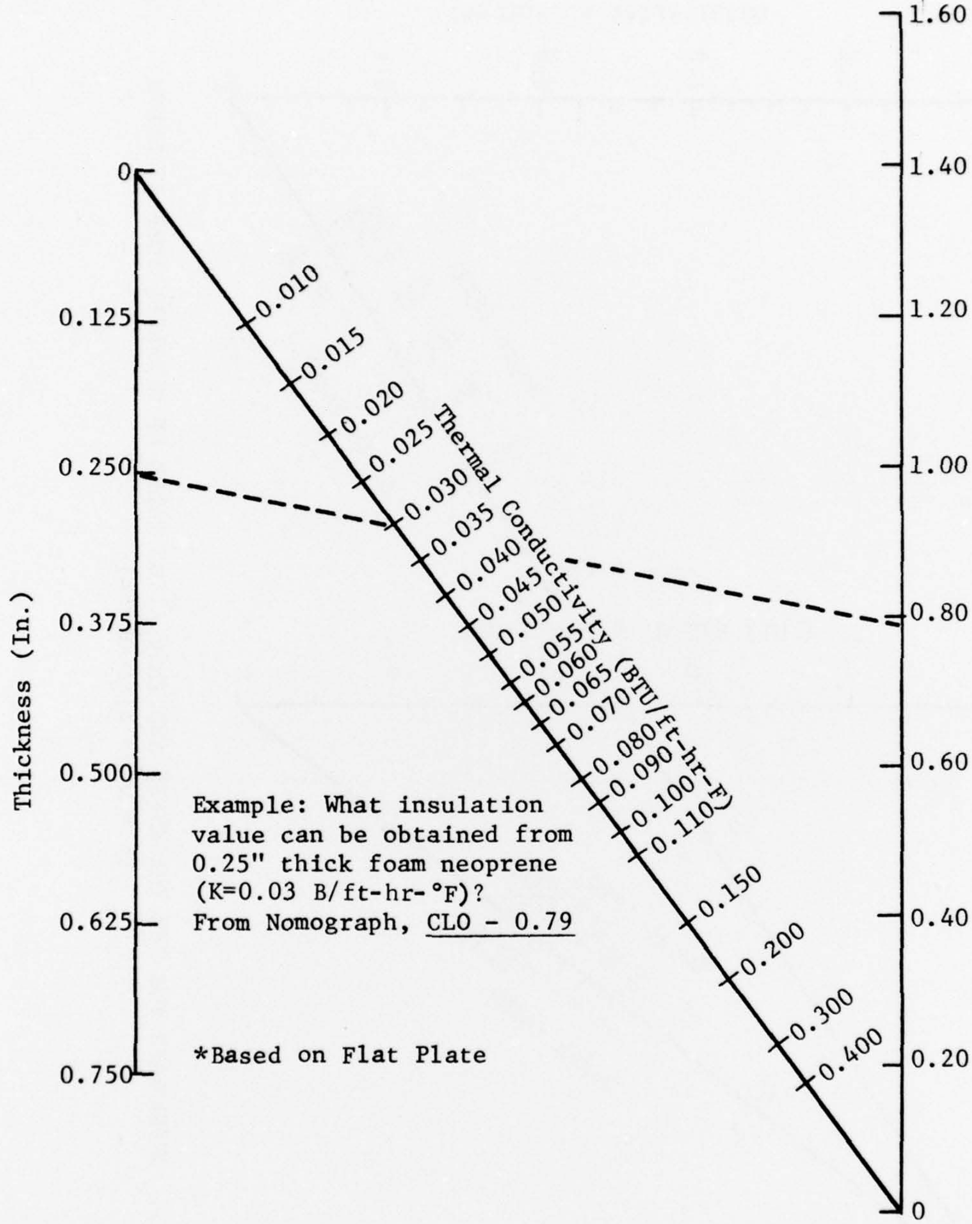

FIGURE A2. *NOMOGRAPH FOR THE INSULATION VALUES OF VARIOUS MATERIALS VERSUS THICKNESS

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